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AEROELASTIC AND STRUCTURES RESEARCH LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TECHNICAL NOTE 75-3

PROPOSED TEST PROGRAM ON AEROTHERMOELASTIC SIMILARITY LAWS

BY
JOHN DUGUNDJI
JOHN M. CALLIGEROS

FOR THE
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
CONTRACT NO. NONR-1841(46)

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ABSTRACT

The similarity laws required for experimental aerothermoelastic studies at $M_\infty < 3.5$ are reviewed. An experimental program to check out some of the concepts and ideas involved in these studies is proposed with particular emphasis on flutter of thin, solid, plate-type lifting surfaces, built-up wing structures, and panel flutter.

LIST OF SYMBOLS

AR	Aspect Ratio
C	Specific Heat of Body Material
c_p	Specific Heat of Gas at Constant Pressure
E	Young's Modulus
G	Shear Modulus
g	Acceleration Due to Gravity
J	Torsional Stiffness Constant
K	Heat Conductivity of Body Material
k	Heat Conductivity of Gas
L	Characteristic Length
M_∞	Free Stream Mach Number
p	Pressure
Pr	Prandtl Number, $\frac{\mu c_p}{k}$
Re_∞	Free Stream Reynolds Number, $\frac{\rho_\infty VL}{\mu_\infty}$
T	Temperature
T_{AW}	Adiabatic Wall Temperature $= T_\infty \left[1 + r \frac{(\gamma-1)}{2} M_\infty^2\right]$
T_{Bi}	Initial Body Temperature
t	Time
u	Displacement Component
V	Free Stream Velocity

LIST OF SYMBOLS (Cont'd)

α	Coefficient of Thermal Expansion
γ	Ratio of Specific Heats
$\bar{\delta}$	Thickness Distribution
ϵ	Emissivity
$\bar{\theta}$	Non-dimensional Temperature $= (T - T_{Bi})/(T_o - T_{Bi})$
κ	Thermal Diffusivity, $\frac{K}{\rho_B C}$
μ	Viscosity of Gas
ν	Poisson's Ratio
ρ	Density
σ	Stefan-Boltzmann Constant
σ	Stress Component
τ	Thickness Ratio

Subscripts

Aw	Adiabatic Wall
B	Relating to Body
F	Relating to non-Aerodynamic Origin
i	Initial Value
O	Reference Value
∞	Free Stream Value

Superscripts

$(\bar{\bar{\ }})$	Non-dimensional, temperature dependent gas or material property variation.

Object

A theoretical study of the similarity laws for aerothermoelastic testing has been made by the Aeroelastic and Structures Research Laboratory at MIT. The results are contained in References 1,2 and particularly 3. It would be of interest now to carry out an experimental test program to check out some of the concepts and ideas involved in these similarity studies. The present note describes such a possible test program that might be undertaken. For simplicity this program will be limited to $M_\infty < 3.5$.

Introduction

As was pointed out in the above mentioned references, similitude for the general aerothermoelastic model is generally not possible for scale ratios other than unity. The primary conflict occurs between the free stream Mach number M_∞, the Reynolds number Re_∞, the basic aeroelastic parameter $\rho_\infty V^2/E_o$, the heat conduction parameter k_∞/K_o, and the thermal expansion parameter $\alpha_o T_o$. However, certain relaxations of this basic conflict are possible when considering specialized situations, such as the behavior of wing structures, thin plate-like lifting surface structures, and panel flutter. Under these conditions the similarity parameters assume less restrictive forms, even permitting geometrical distortions in some cases.

In the event that similarity is not achievable under these specialized situations, recourse may be made to "incomplete aerothermoelastic testing" in which the pressure and/or thermal loadings are estimated in advance and applied artificially to the model. This is in contrast to the previous complete aerothermoelastic testing where the high stagnation temperature air stream provides both the appropriate aerodynamic pressure loads and heating rates to the model.

Finally, if not much coupling is evident between the aerodynamic pressure, aerodynamic heating, heat conduction, and stress and deflection phenomena, one can construct "restricted purpose" models investigating separately one or another of the above facets of the complete aerothermoelastic problem.

Since both "restricted purpose" models and "incomplete aerothermoelastic testing" have been widely used and studied in the past, the present test program will attempt to deal with the more novel specialized situations of the complete aerothermoelastic problem.

In proposing such an aerothermoelastic test program, it is desirable to select situations where aerothermoelastic coupling effects are pronounced. The following situations have accordingly been selected:

1) Flutter of heated solid section wings
2) Flutter of heated built-up wings
3) Flutter of heated panels

In addition to checking out the aerothermoelastic similarity relations, the present program can also serve to investigate the aerothermoelastic phenomena involved, and the theory developed to predict it.

Review of the Similarity Parameters

a) General Aerothermoelastic Body

The similarity parameters for a general aerothermoelastic model at $M_{\infty} < 3.5$ are essentially (Ref. 1, Eq. 2.35

and Ref. 3, Eq. 52)

$$M_\infty,\ Re_\infty;\ \frac{\rho_\infty V^2}{E_o},\ \frac{k_\infty}{K_o},\ \alpha_o T_o,\ \frac{\rho_B}{\rho_\infty},\ \frac{T_o}{T_\infty},$$

$$\frac{K_o t_o}{L^2},\ \frac{V t_o}{L},\ \frac{u_o}{L},\ \frac{\sigma_o}{E_o},\ \frac{p_F}{E_o},\ \frac{\epsilon_o \sigma T_o^3 L}{K_o},\ \frac{\rho_B g L}{\rho_\infty V^2}, \tag{1}$$

$$Pr,\ \gamma,\ \nu,\ \bar{\bar{k}},\ \bar{\bar{c}}_p,\ \bar{\bar{\mu}},\ \bar{\bar{K}},\ \bar{\bar{G}},$$

$$\bar{\bar{E}},\ \bar{\bar{\alpha}},\ \bar{\bar{\epsilon}},\ \frac{T_{Bi}}{T_o}$$

The first five parameters above are the primary ones to be reconciled. The ρ_B/ρ_∞ condition is required only in dynamic aerothermoelastic problems such as flutter, and often there it may be neglected at sufficiently large values of ρ_B/ρ_∞. The next five parameters serve to define the reference values of T_o, t_o, u_o, and σ_o to be used in the nondimensionalizations*. The p_F/E_o condition defines any additional non-aerodynamic loads present. The $\epsilon_o \sigma T_o^3 L/K_o$ and $\rho_B g L/\rho_\infty V^2$ conditions enter only when surface radiation effects and gravity effects are significant, while the next three conditions can usually be satisfied by many gases and materials. The remaining double-barred quantities are all functions of temperature and require that they have the same variation for model and prototype. The T_{Bi}/T_o calls for similarity of body initial temperature states.

If the above parameters are satisfied, then the nondimensional quantities $P/\rho_\infty V^2$, T/T_o t/t_o, u/u_o and $\dot{\sigma}/\dot{\sigma}_o$

*The presence of the two reference times t_o need not be bothersome if thermal times are considerably different from aerodynamic times.

will be the same for model and prototype, and behavior of the model may infer behavior of the prototype. References 1 and 3 give a discussion of the use of different materials and gases to satisfy the above requirements.

Similitude under the conditions of Eq. (1) is generally not possible for scale ratios other than unity. The following specialized aerothermoelastic problems were therefore also studied in which it is shown that several of the parameters of the general problem above appear in less restrictive combined forms.

b). Wing Structures

For the specialized situation of wing structures, the similarity parameters of Eq. (1) reduce essentially to (Ref. 1, Eq.4.8 and Ref. 3, Eq. 58)

$$M_\infty,\ \frac{k_\infty (Re_\infty)^{.8}(P_r)^{1/3}}{K_o},\ \frac{\rho_\infty V^2}{E_o},\ \alpha_o(T_o - T_{Bi}),\ \frac{\rho_B}{\rho_\infty},\ \frac{T_o - T_{Bi}}{T_{Aw} - T_{Bi}},$$
$$\frac{K_o t_o}{L^2},\ \frac{V t_o}{L},\ \frac{u_o}{L},\ \frac{\sigma_o}{E_o},\ \frac{P_F}{E_o},\ \frac{\epsilon_o \sigma L\left[(T_o - T_{Bi})\bar{\theta} + T_{Bi}\right]^4}{K_o(T_o - T_{Bi})}, \quad (2)$$
$$\frac{\rho_B g L}{\rho_\infty V^2},\ \gamma,\ \nu,\ \bar{\bar{k}},\ \bar{\bar{c}}_p,\ \bar{\bar{\mu}},\ \bar{\bar{K}},\ \bar{\bar{C}},\ \bar{\bar{E}},\ \bar{\bar{\alpha}},\ \bar{\bar{\epsilon}}.$$

The parameters above are less restrictive than the general case since $k_\infty (Re_\infty)^{.8} (Pr)^{1/3} / K_o$ above is a combination of the Re_∞, k_∞/K_o and Pr conditions of Eq. (1). This parameter results from the application of Prandtl's boundary layer concept to the flow close to the body region. Turbulent flow is assumed above (if laminar then the second parameter is replaced here and throughout by $k_\infty (Re_\infty)^{.5}(Pr)^{1/3}/K_o$). The parameter $(T_o - T_{Bi})/(T_{Aw} - T_{Bi})$ now serves to define the reference temperature T_o. The non-dimensional temperature $\bar{\theta}$ is now defined as $(T - T_{Bi})/(T_o - T_{Bi})$ rather than the T/T_o of the general case a), therefore eliminating problems in maintaining cumbersome uniform initial temperature conditions on the models.

A further simplification can be made at early times, when only the skin heats up and not much heat has been conducted to the webs. Under these conditions and with the assumption that heat flow in the plane of the thin skin is negligible, the second and seventh parameters above combine into the less stringent parameter.

$$\frac{k_\infty (Re_\infty)^{.8} (P_r)^{1/3} t_o}{\rho_B C_o L^2} \tag{3}$$

Under these conditions it is seen that the Reynolds number Re_∞ merely serves to redefine the reference time t_o. This eliminates the primary obstacle in the scaling laws and any scale length may now be accommodated.

c) Thin, Solid, Plate-Type Lifting Surfaces

The parameters of Eq. (1) are further reduced to the following less restrictive forms when considering affinely related thin, solid, plate-type lifting surfaces (Ref. 2, Eq. 5.11, 2.34, 3.12, etc., and Ref. 3, Eq. 63)

$$\begin{gathered}
\sqrt{M_\infty^2 - 1}\,\tau,\quad \frac{k_\infty (Re_\infty)^{.8} (P_r)^{1/3}}{K_o \tau},\quad \frac{\rho_\infty V^2}{E_o \tau^2},\quad \frac{\alpha_o (T_o - T_{Bi})}{\tau^2},\quad \frac{\rho_B}{\rho_\infty}, \\
\frac{T_o - T_{Bi}}{T_{Aw} - T_{Bi}},\quad \frac{\kappa_o t_o}{L^2},\quad \frac{V t_o}{L},\quad \frac{u_o}{L\tau},\quad \frac{\sigma_{o\circ}}{E_o \tau^2},\quad \frac{P_F}{E_o \tau^4}\left(\frac{L\tau}{u_o}\right), \\
\frac{\epsilon_o \sigma L [(T_o - T_{Bi})\bar{\theta} + T_{Bi}]^4}{K_o \tau (T_o - T_{Bi})},\quad \frac{\rho_B g L \sqrt{M_\infty^2 - 1}}{\rho_\infty V^2}\left(\frac{L\tau}{u_o}\right),\ \gamma,\ \nu, \\
\bar{\bar{k}},\quad \bar{\bar{\mu}},\quad \bar{\bar{K}},\quad \bar{\bar{C}},\quad \bar{\bar{E}},\quad \bar{\bar{\alpha}},\quad \bar{\bar{\epsilon}},\quad \bar{\delta}
\end{gathered} \tag{4}$$

where τ is the thickness ratio. These parameters are applicable for large deflections and it is assumed that the heat flow into the thin plate-like surface causes a very small temperature variation through the thickness.

The parameters above are less restrictive than Eq. (1) because of their combined forms involving τ. If small deflections are assumed and if additionally piston theory can be assumed for the aerodynamic loading, the reference parameter $u_o/L\tau$ does not appear separately in Eq. (4) and u_o becomes a free quantity.

The scaling requirements are further simplified if it can be assumed that heat flow in the plane of the plate-like surface is negligible. In this case the following parameter replacing the second and seventh conditions of Eq. (4) results

$$\frac{k_\infty (Re_\infty)^{.8} (P_r)^{1/3} t_o}{\rho_B C_o \tau L^2} \qquad (5)$$

where again it is seen that Re_∞ will serve only to redefine the reference time t_o.

d) Panel Flutter

The parameters of Eq. (1) reduce essentially to the following for the flutter of thin heated panels undergoing large deflections (Ref. 1, Eq. 4.30, Ref. 2, Eq. 4.19, and Ref. 3, Eq. 70)

$$\frac{\rho_\infty V^2}{E_o \tau^3 \sqrt{M_\infty^2 - 1}}, \quad \frac{k_\infty (Re_\infty)^{.8} (P_r)^{1/3}}{K_o \tau}, \quad \frac{\alpha_o (T_o - T_{Bi})}{\tau^2}, \quad \frac{\rho_B \sqrt{M_\infty^2 - 1}\, \tau}{\rho_\infty},$$

$$\frac{T_0 - T_{Bi}}{T_{Aw} - T_{Bi}}, \quad \frac{\kappa_0 t_0}{L^2}, \quad \frac{V t_0}{L}, \quad \frac{u_0}{L\tau}, \quad \frac{\sigma_0}{E_0 \tau^2}, \quad \frac{p_F}{E_0 \tau^4}\left(\frac{L\tau}{u_0}\right), \tag{6}$$

$$\frac{\epsilon_0 \sigma L \left[(T_0 - T_{Bi})\bar{\theta} + T_{Bi}\right]^4}{K_0 \tau (T_0 - T_{Bi})}, \quad \frac{\rho_B g L \sqrt{M_\infty^2 - 1}\left(\frac{L\tau}{u_0}\right)}{\rho_\infty V^2}, \quad \nu, \ \bar{\bar{k}}, \ \bar{\bar{\mu}}$$

$$\bar{\bar{K}}, \ \bar{\bar{G}}, \ \bar{\bar{E}}, \ \bar{\bar{\alpha}}, \ \bar{\bar{\epsilon}}$$

where τ is the thickness ratio of the panel. The absence of $\sqrt{M_\infty^2 - 1}\,\tau$ is to be noted since now there are no aerodynamic thickness effects. For small deflections, the deflection parameter $u_o / L\tau$ will not appear separately above in Eq. (6).

As in the case of the thin solid lifting surface of section c , the second and sixth parameters above combine into the single parameter of Eq. (5) if heat conduction in the plane of the panel is negligible.

EXPERIMENTAL TEST PROGRAM

a) Flutter of Thin, Solid, Plate-Type Lifting Surfaces

It is proposed to test three similar wings of different scale in a large, high stagnation temperature wind tunnel at $M_\infty = 3$. Their aerothermoelastic behavior, principally flutter, is to be correlated according to the specialized parameters of section c above.

The wings are to be rectangular in planform, of solid double wedge cross section with $\tau = .03$, $AR = 3$ and maximum thickness at seventy percent chord. The tunnel stagnation temperature should be approximately 500°F and the wings constructed of stainless steel 17-7 PH for strength and minimum change in material properties with temperature. This latter consideration would provide a better indication of the direct effect of thermal stresses in reducing the torsional stiffness of the wing. For such wings, the dynamic pressure, $\rho_{\infty} V^2/2$, at flutter is approximately 3800 lbs/ft^2 and the maximum reduction in GJ is approximately 70% according to the theory of Budiansky and Mayers (Ref. 4). In order to minimize the starting loads on the wing, it may be provided either with a flexible root, injected into the test section after flow has been established or provided with a protective cover shell which will take the starting loads and then become disengaged after the flow has been established. This latter method has been used by the NASA in their 6' x 9' , $M_{\infty} = 3$, thermal tunnel.

Models of different scale are suggested so that the influence of the Reynolds number appearing in the second parameter of Eq. (4) may be ascertained. It is also of particular interest to see if correlation is possible with the parameter of Eq. (5). If so, the effect of a change in length scale at fixed free stream conditions would be to merely change the actual time of occurrence of the aerothermoelastic phenomena being investigated.

The flutter test procedure would be to first establish the cold flutter dynamic pressure of these wings by testing at room stagnation temperatures. Then one could run at some lower $\rho_{\infty} V^2/2$ but higher stagnation temperature and observe the time to flutter for each of these wings.

The models could also be instrumented to measure temperature and root strains and correlation again attempted using the parameters of Eqs. (4) and (5). In addition to correlating similarity parameters, the above tests would provide an experimental check of Budiansky and Mayers' theory of thermal stress effects (Ref. 4) on basic aeroelastic flutter.

The effect of using different materials may be investigated by using one of the 17-7 PH steel wings above as a prototype and an identical wing constructed of aluminum 2024 as the model. According to Eqs. (4) and (5) above, similarity may be achieved using a lower stagnation temperature such that $\alpha_o(T_o - T_{Bi})$ was maintained. The corresponding dynamic pressure for the aluminum model would be about 1/3 as great as the steel prototype.

The effect of using a different thickness ratio τ could be investigated. This would then require testing at a different Mach number to maintain the same $M_\infty \tau$, and at a different stagnation temperature. Again correlation with the basic 17-7 PH steel wing as a prototype could be attempted, in both flutter speeds, time to flutter, and temperature time histories.

This proposed experimental program was discussed with the personnel of the Structures Research Division and Dynamic Loads Division of the NASA at Langley Field, Virginia. As a result of discussions there, it is recommended that tests be conducted also on flat plate delta and swept wing planforms similar in nature to the tests described above for the rectangular wings. Some of their current tests on such delta wings are along similar lines as described here and it is anticipated that when more data is available correlation will be attempted according to the parameters described here.

b) Flutter of Heated Built-Up Wings

In this program, it is proposed to again place three different scale built-up wing sections in a large, high stagnation temperature $M_\infty = 3$ tunnel, and to correlate aeroelastic behavior.

The suggested wings could be of typical X-15 type construction. In this case, there is not expected to be a marked decrease in GJ due to thermal effects. Probably here, only temperatures or static tip twists as influenced by temperature could be measured.

Another program that might be of interest to undertake here would be to build three different scale models of the chordwise type flutter observed originally in Reference 5. The time to flutter for these different scale models might possibly be correlated according to the parameters of Eqs. 2 and 3.

c) Flutter of Heated Panels

In this program, it is proposed to place three similar panels of differing scale in a high stagnation temperature tunnel. Again, the correlation of the flutter behavior and time to flutter of the different size panels could be attempted according to the parameters of Eq. 6. Different materials as well as different thickness ratios and stagnation temperatures could be tried for correlation as previously suggested in the flutter of heated solid section wings.

In this connection, the interesting phenomenon of heated panels first fluttering and then stopping after buckling is produced might possibly be examined. As reported in Ref. 6 the times to start and stop fluttering might possibly be correlated. For the stopping behavior of this flutter, the large deflection parameters would no doubt have to be used.

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